Development and Validation of Crack Growth Models and Life Enhancement Methods for Rotorcraft Damage Tolerance

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Objectives

- Develop models for predicting influence of residual stresses on fatigue crack growth and validate by tests on cold-worked holes

- Determine optimum residual stress profiles for fatigue resistance components

Roles and Responsibilities

- Sikorsky Aircraft
  - Document industry practice for fatigue life enhancement
  - Acquisition and preparation of fatigue test specimens
  - Model fatigue crack growth using superposition method
  - Perform fatigue crack growth testing

- Mississippi State University
  - Research current and new fatigue life enhancements
  - Perform fatigue crack growth testing
  - Model fatigue crack growth using finite-element analyses
  - Model fatigue crack growth using strip-yield model
  - Model fatigue crack growth using superposition method

Technical Approach

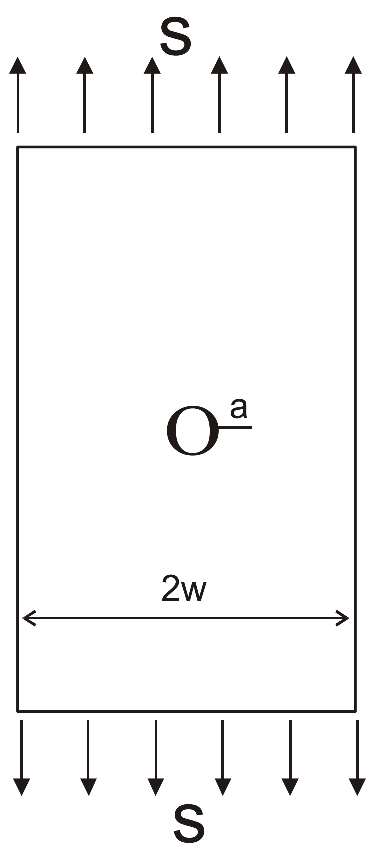
- Fatigue crack growth simulation using finite element analysis, FASTRAN, and elastic superposition
- Conduct fatigue crack growth tests in specimens with and without cold-work
- Optimum residual stress profiles for fatigue resistance components will be characterized

Expenditures

Total expenditures as of 10/31/04 $307K

	budgeted	encumbered	available
MSU	$215K	$207K	$8K
Sikorsky	$195K	$100K	$95K

Fatigue Crack Growth Data

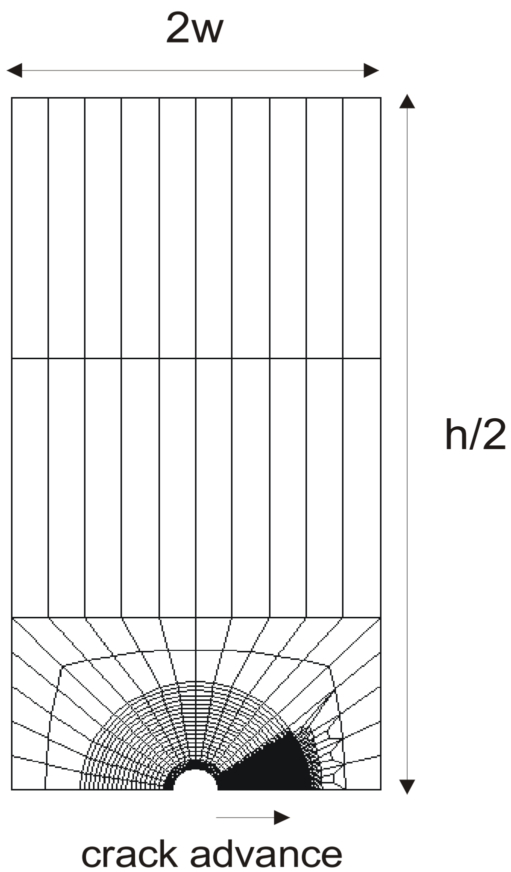


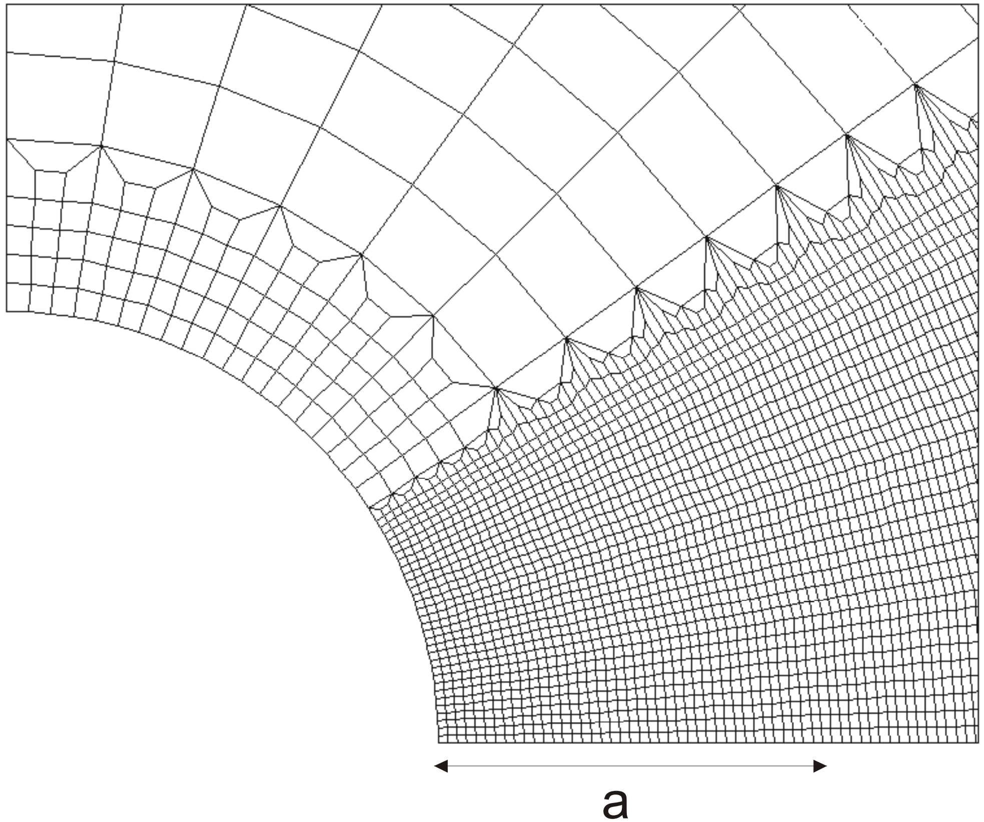
A.F. Liu, Northrop Corp., 1979
AA 2024-T351 Y = 54 ksi
W = 3 in, D = 0.75 in, t = 0.258 in
R = 0.10

residual stress induced by single overload S_{max} = 36 ksi

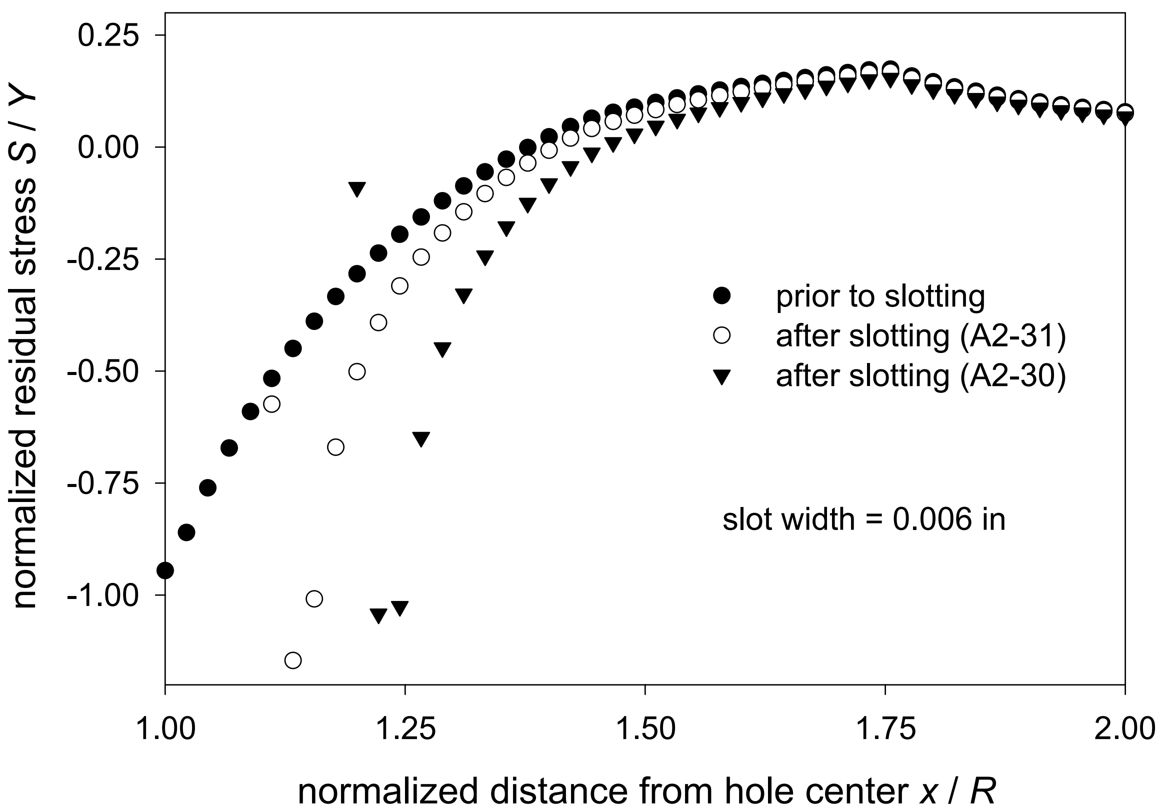
A2-31: S = 18 ksi 0.0405 inch slot
A2-30: S = 15 ksi 0.0720 inch slot

Finite Element Model

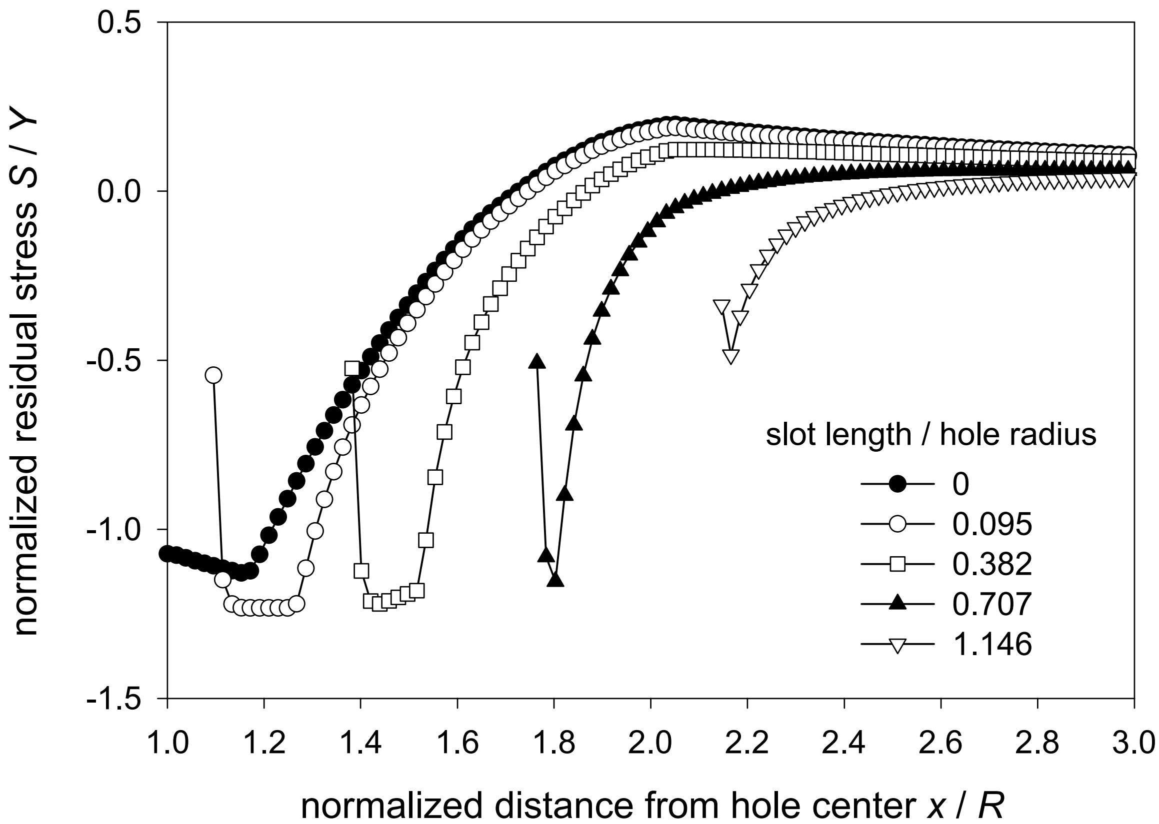




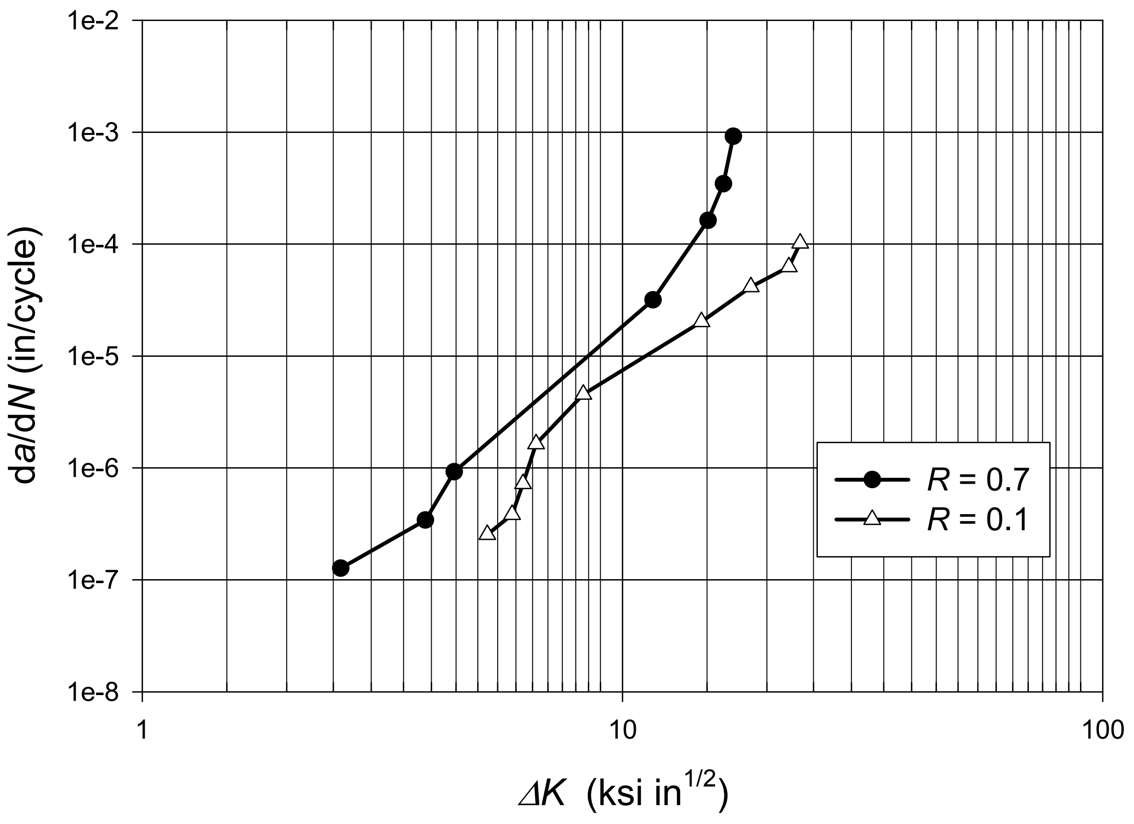
Redistribution of Residual Stress Due to Slotting



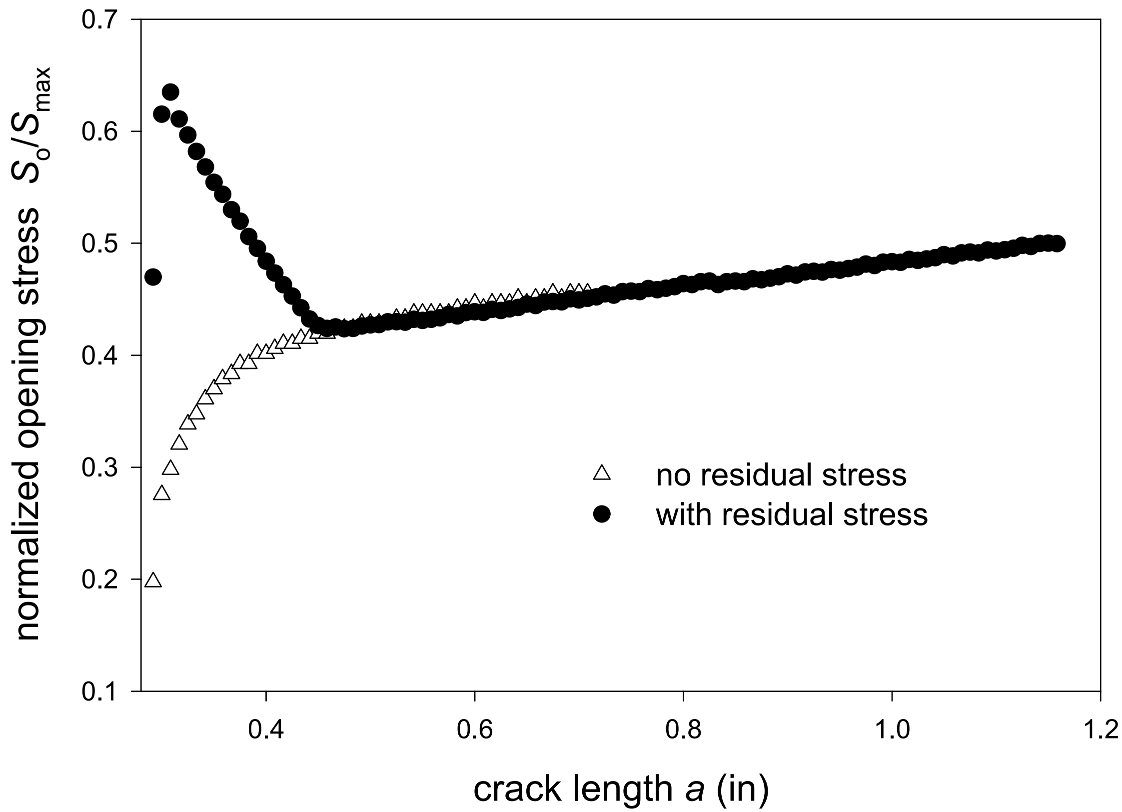
Redistribution of Cold Work Residual Stress



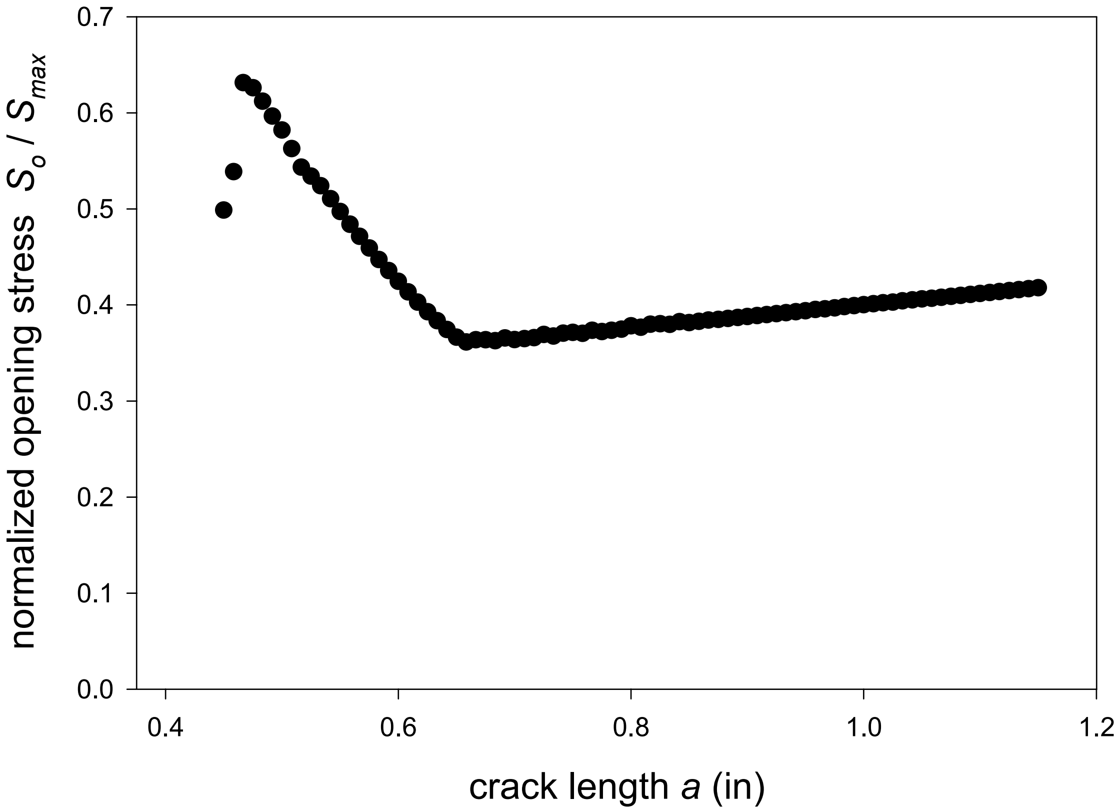
2024 Fatigue Crack Growth Data from Liu



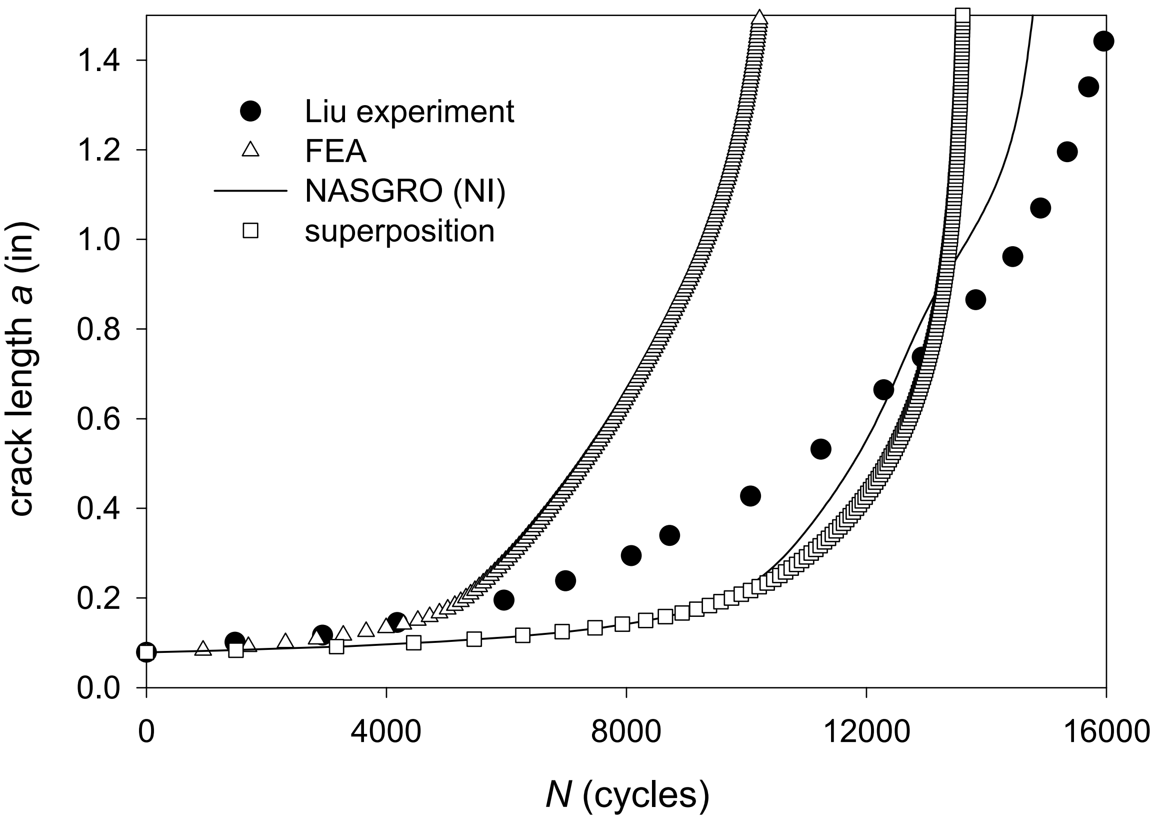
Predicted Crack Opening Stress (A2-31)



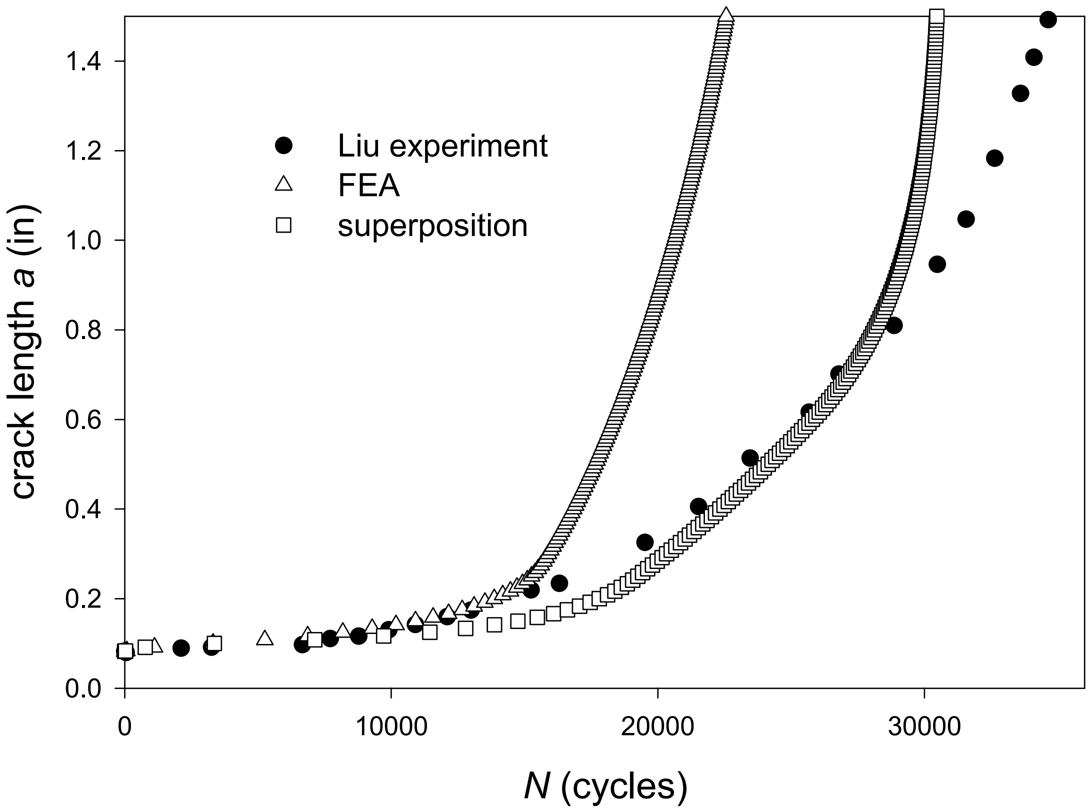
Predicted Crack Opening Stress (A2-30)



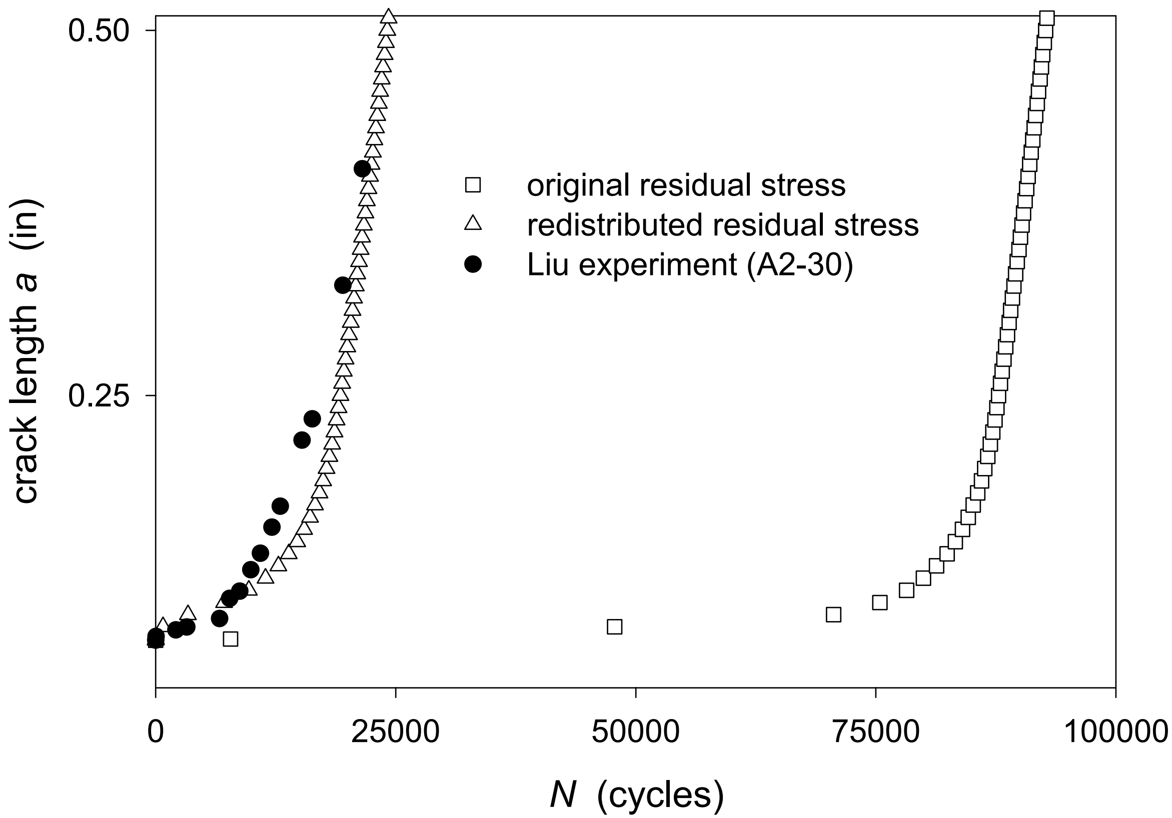
Fatigue Crack Growth (A2-31)



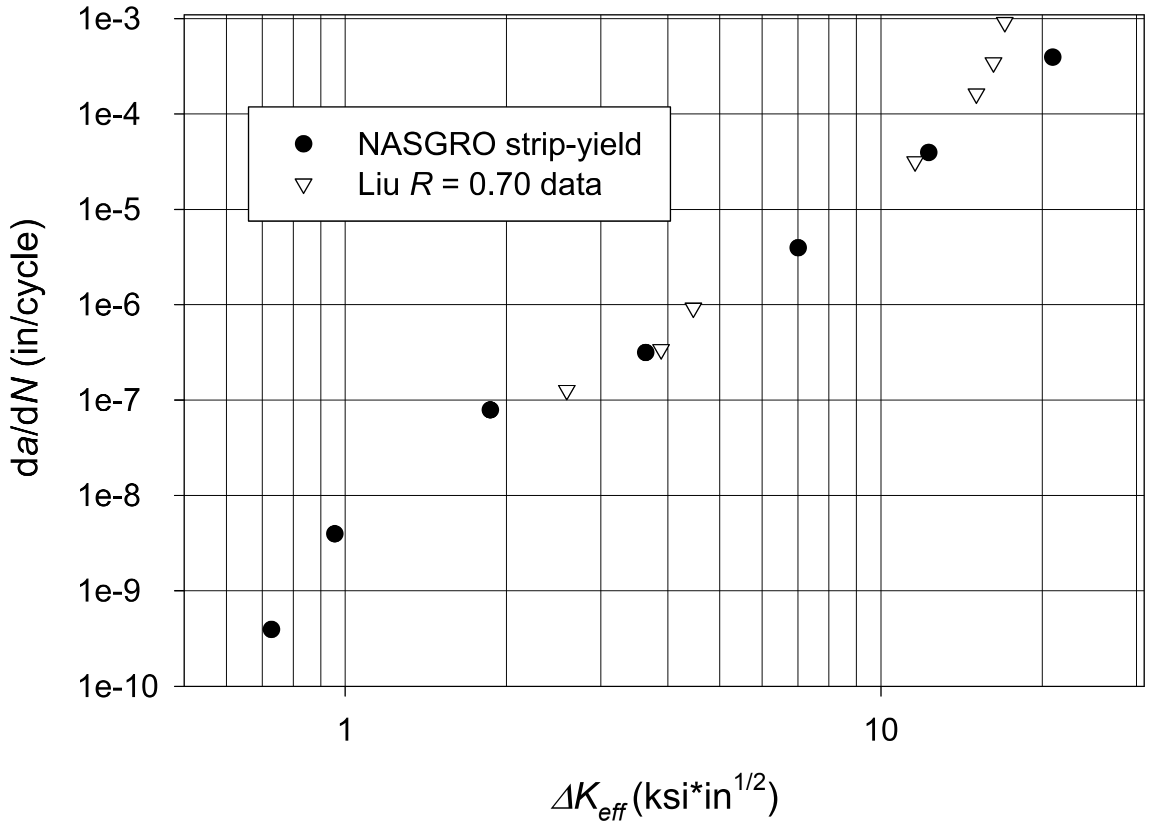
Fatigue Crack Growth (A2-30)



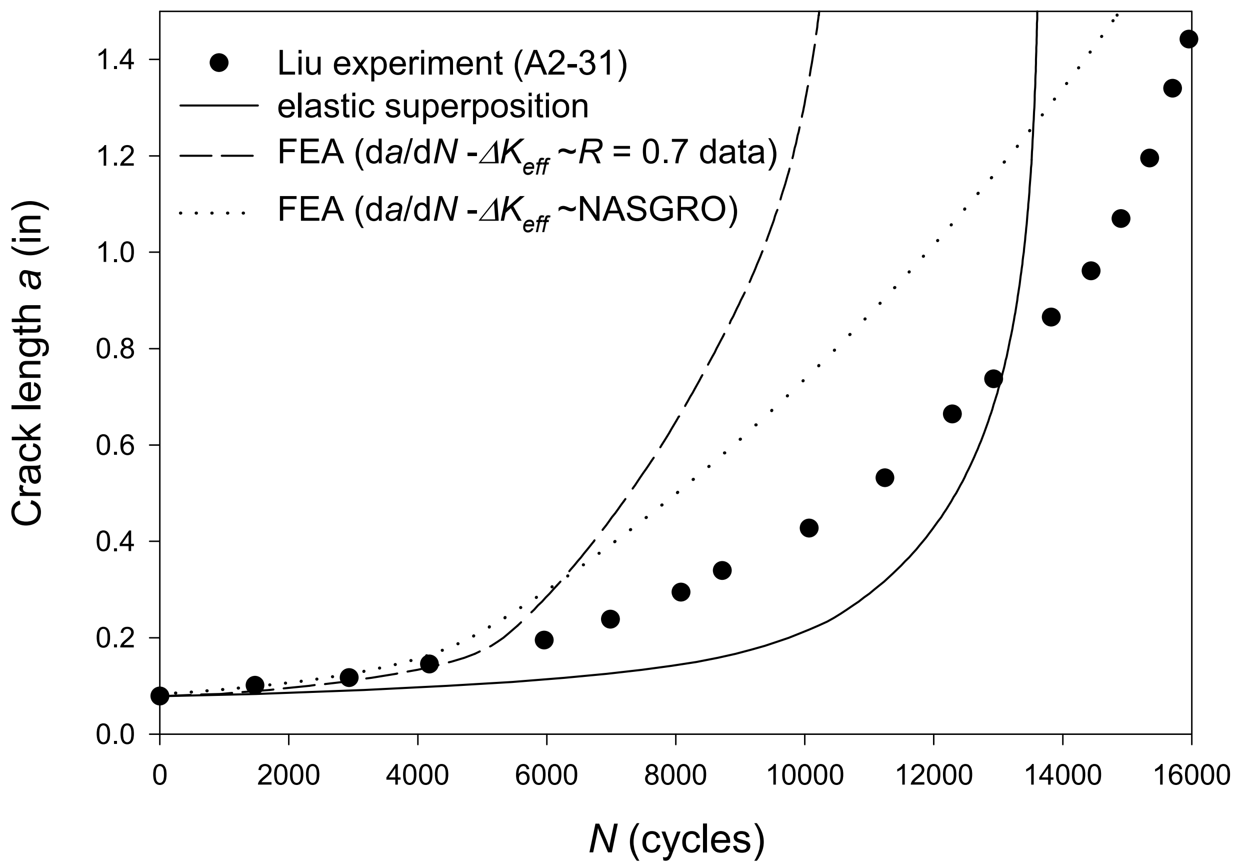
FCG Predictions Using Superposition



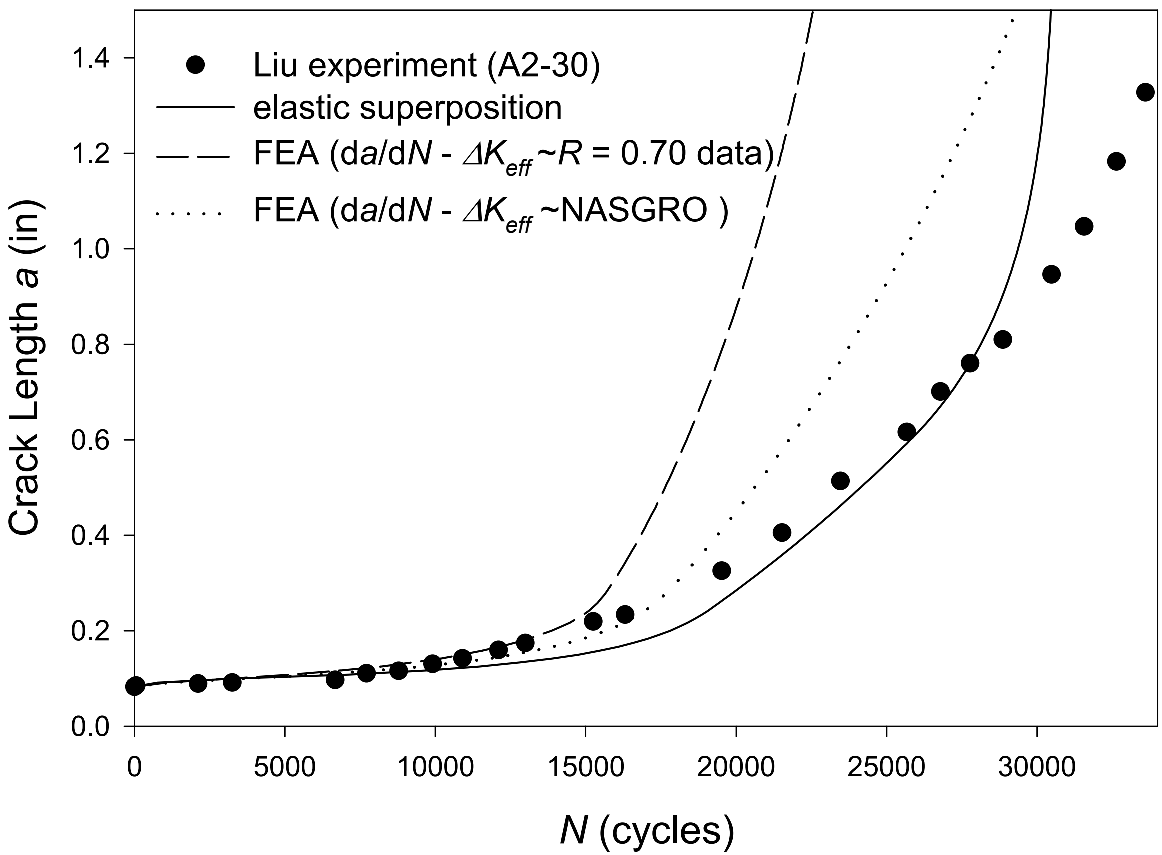
2024 Fatigue Crack Growth Data



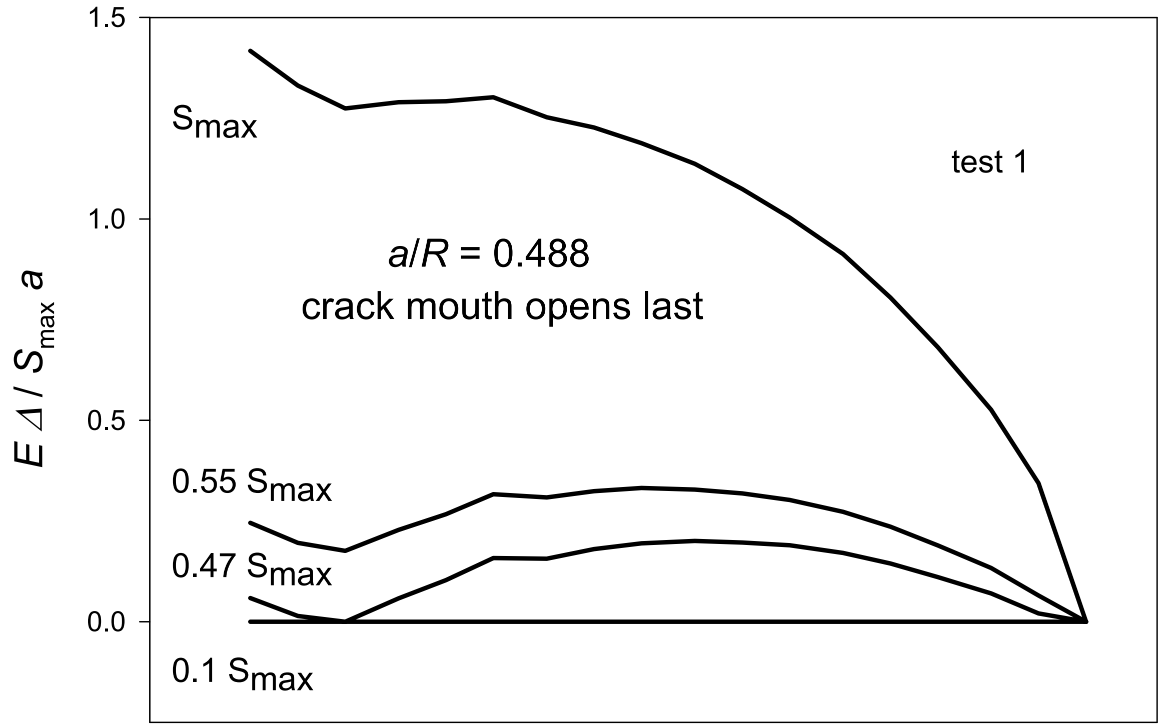
Fatigue Crack Growth (A2-31)



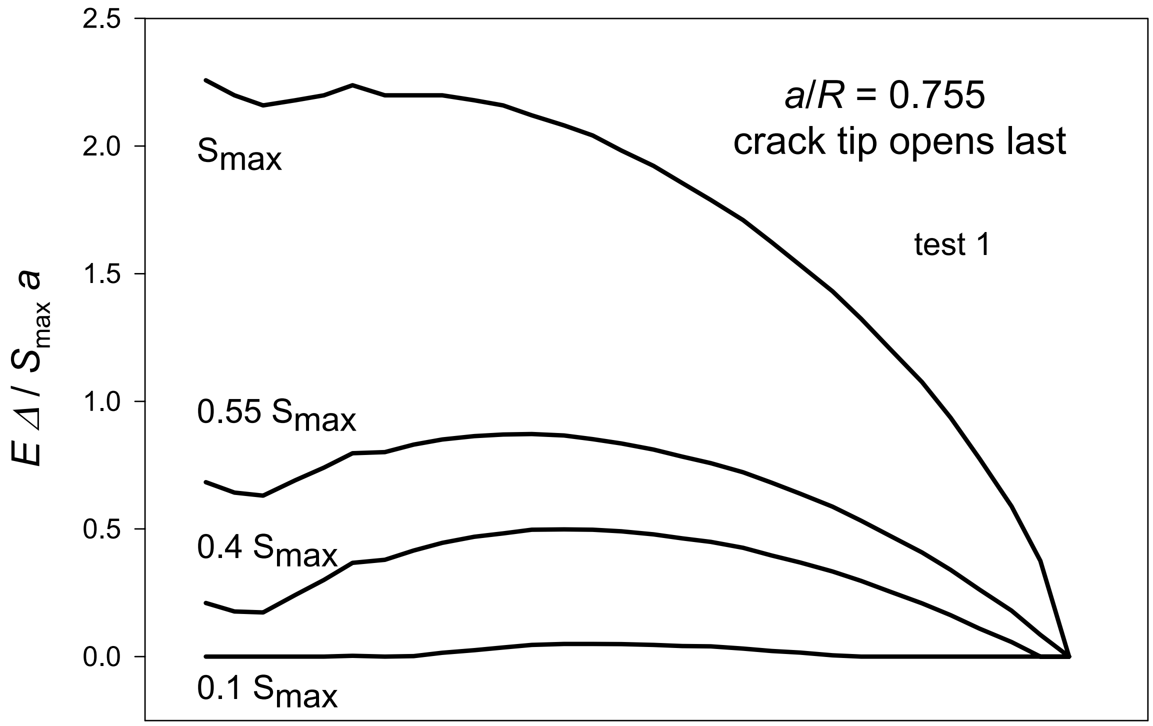
Fatigue Crack Growth (A2-30)



Crack Opening Profile
small crack



Crack Opening Profile
large crack



Research Results

- elastic superposition is simple AND accurate
- superposition requires an accurate residual stress distribution
- elastic-plastic FEA simulations very sensitive to da/dN – ΔK_{eff} curve used

Technical Issues / Concerns

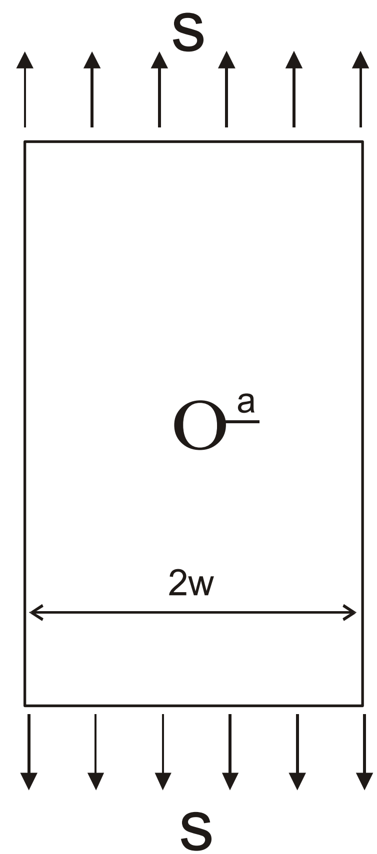
- more FCG data needed for validation
- completion of fatigue crack growth testing

Planned Research

- Use fatigue crack growth data to further validate models
- Determine optimal residual stress distribution for FCG resistance

Fatigue Crack Growth Experiments

- AA 7075-T6
  (*B* = 0.08 and 3/16 inch)
- constant-amplitude loading
- through-crack at hole
- part-through crack at hole
- with and without cold working



BACKGROUND

Elastic Superposition Approach

$$K = (K)_{\mathrm{loading}} + (K)_{\mathrm{residual}}$$

if $K < 0$ then take $K = 0$

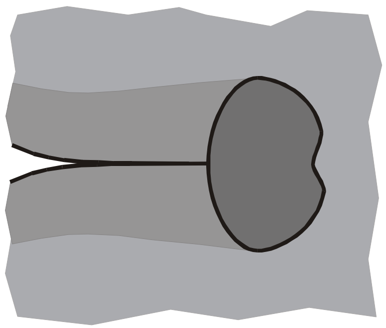
$$da/dN = f\,(\Delta K)$$

- residual stress not altered by crack growth
- simple elastic perspective
- $(K)_{\mathrm{residual}}$ from weight function integration

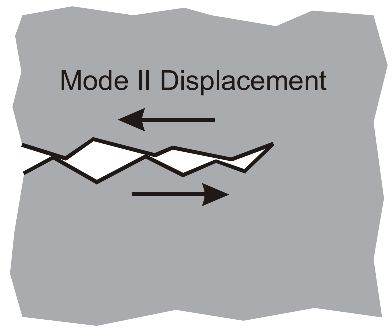
Physics Based Approach

- residual stress will redistribute as crack grows
- crack tip plasticity not ignored
- wake of plastically deformed material left behind growing crack

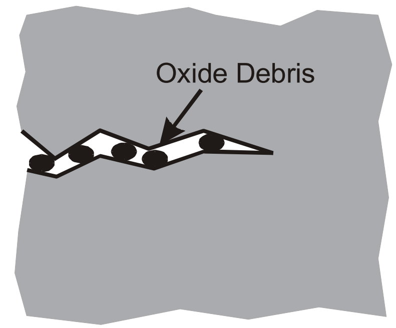
Crack Closure Mechanisms



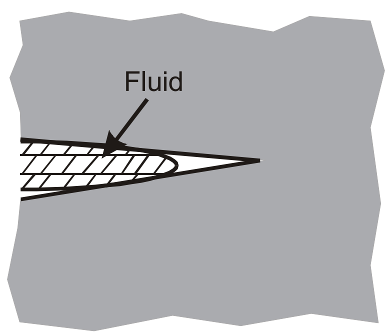
Plasticity-Induced



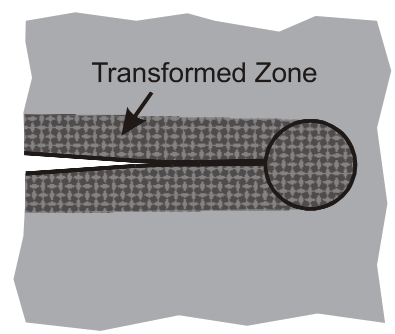
Roughness-Induced



Oxide-Induced



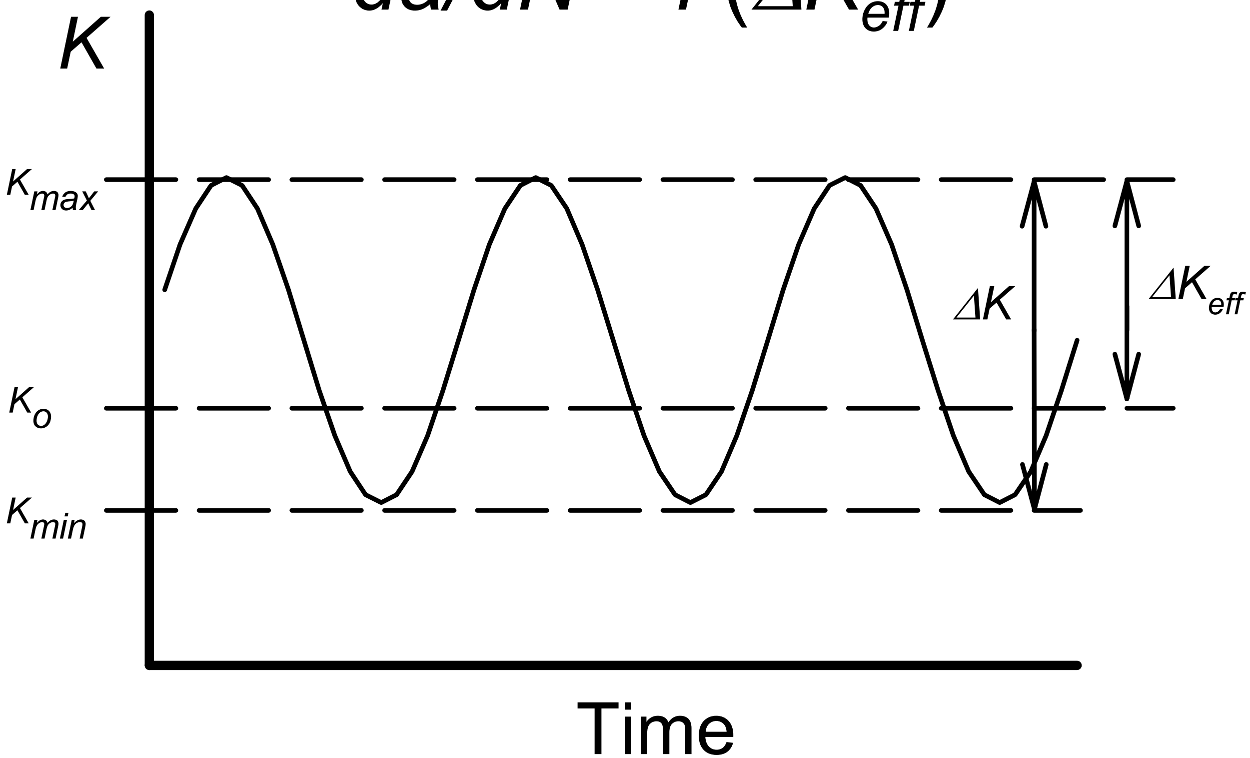
Viscous Fluid Induced



Transformation-Induced

Effective Crack Driving Force

$$da/dN = f\,(\Delta K_{eff})$$

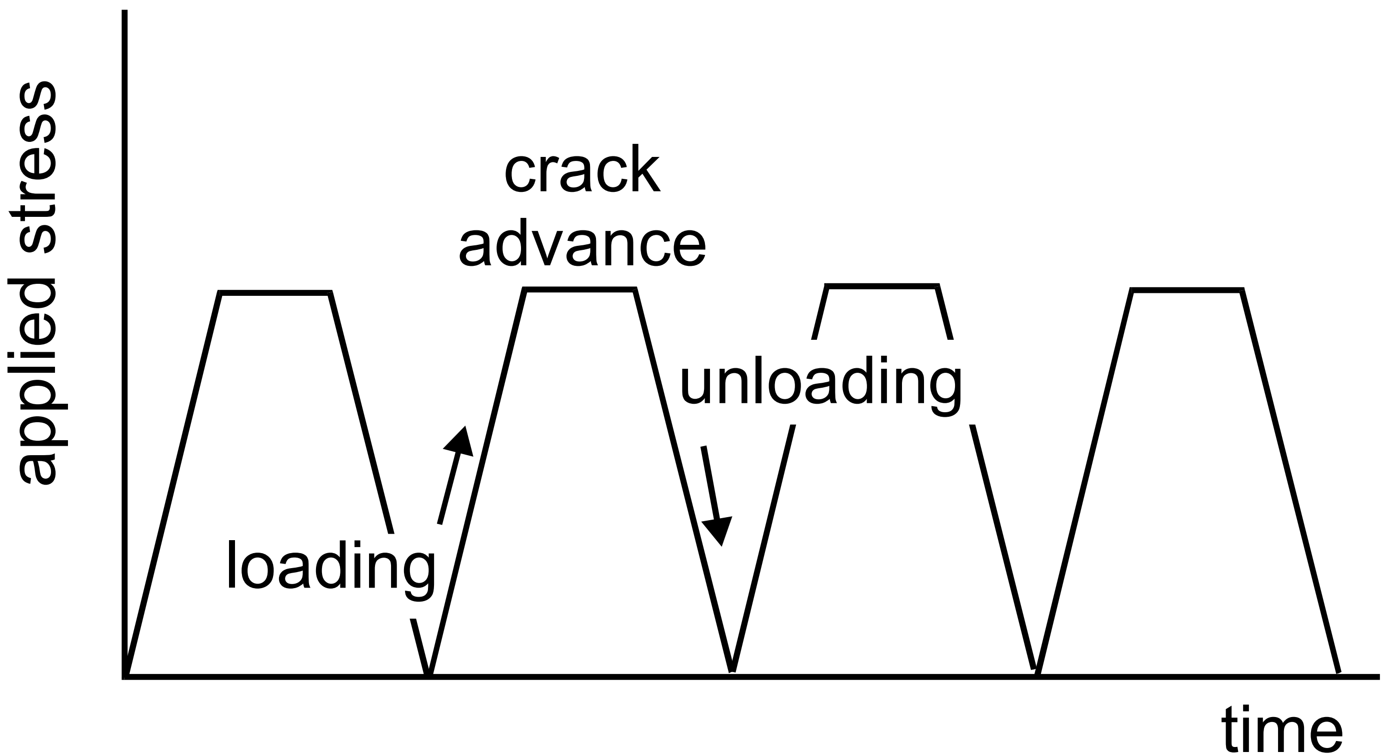


Elastic-Plastic Finite Element Analyses

- determine residual stress redistribution due to slotting
- include effects of further residual stress redistribution as crack grows
- compute crack opening stress

Simulation of Crack Growth

each load cycle = 3 FE analyses



Analysis Methodology

compute crack opening stress S_o

compute ΔK_{eff}

use material property

$da/dN = f\,(\Delta K_{eff})$

compute dN

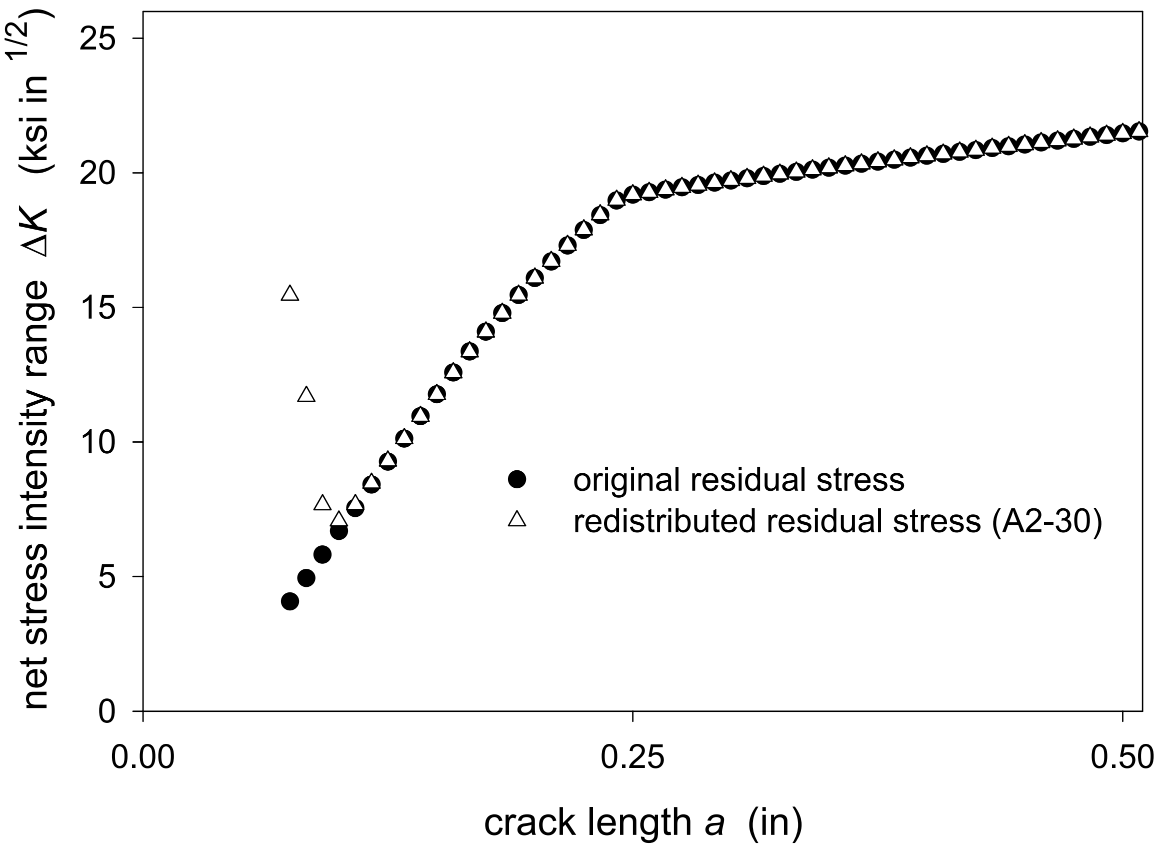
$dN = da/\,f\,(\Delta K_{eff})$

update

$a = a + da$

$N = N + dN$

ΔK Calculation Using Superposition



Test Specimen Description

Non-cold worked specimens:

7075-T6 aluminum sheet

1.750” x .080” x 8.0” (.010” deep thru notch),

1.750” x .190” x 8.0” (.030” deep corner notch)

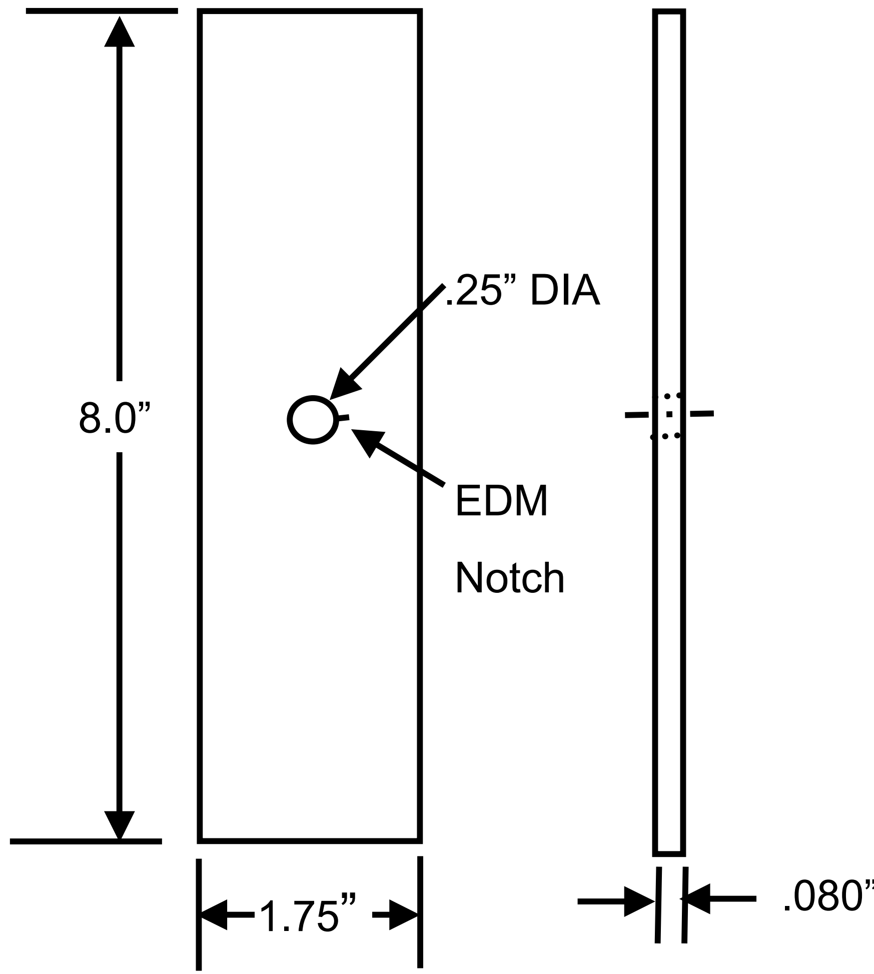
.250” DIA reamed hole with breakedge

Cold worked specimens:

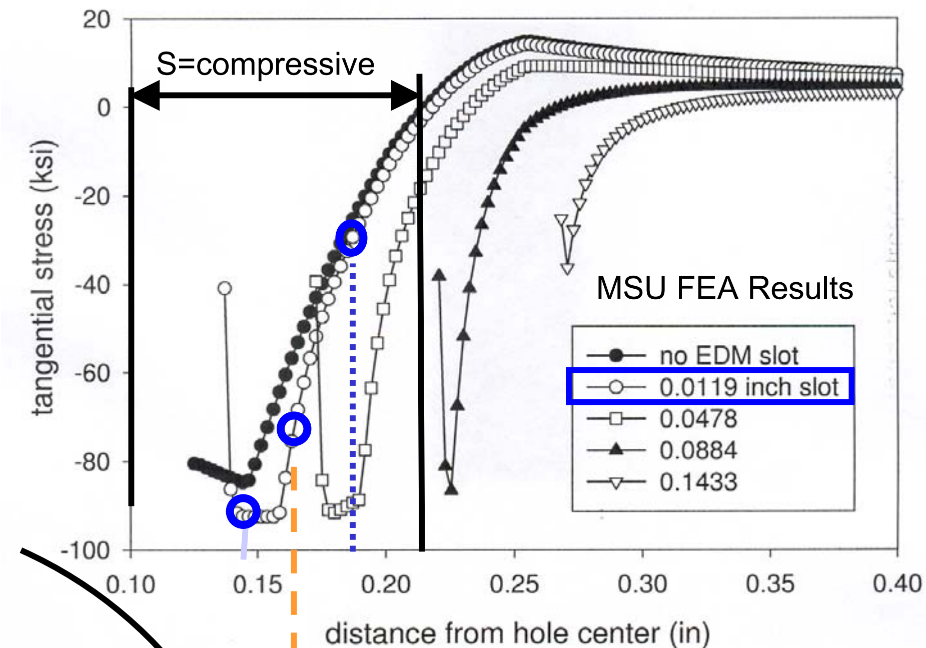
Reamed hole DIA: .270, .312, .344

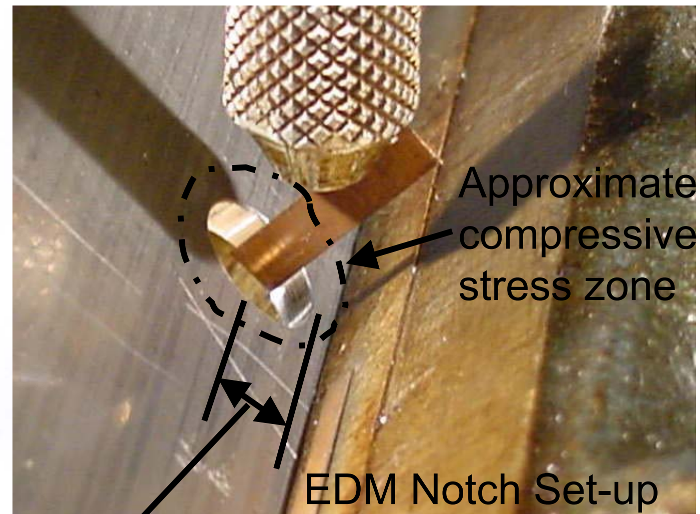
Polished edges and surface at notch

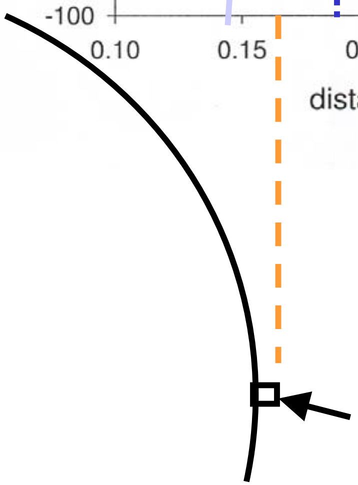
Nylon shims



Cold-worked Specimens: Methodology and Results







EDM notch at edge of hole
(magnified view)

Distance from hole center:

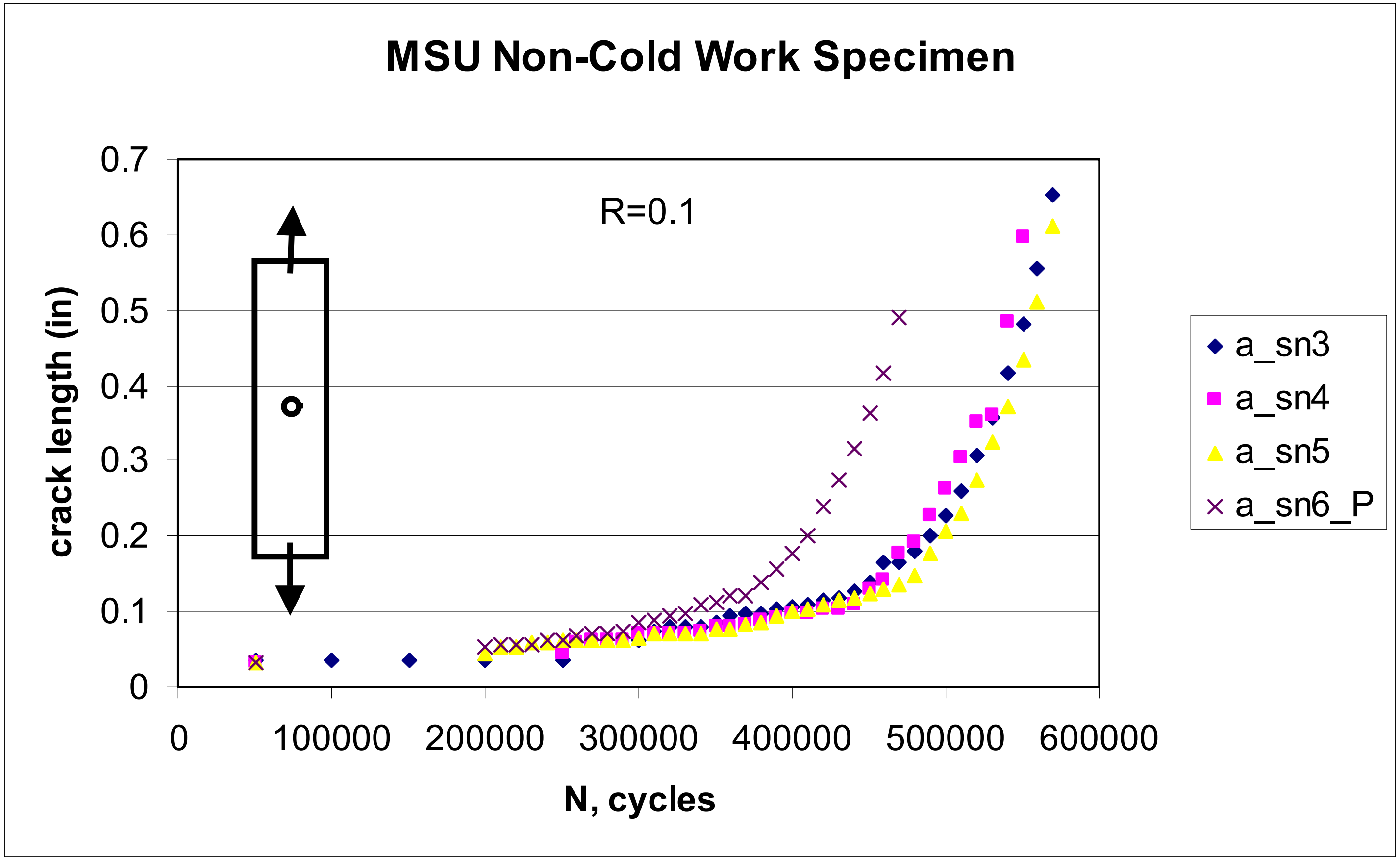
Hole radius + EDM notch = distance

.270/2 +.010 =.145” (.02” crack at 2e6 cycles)

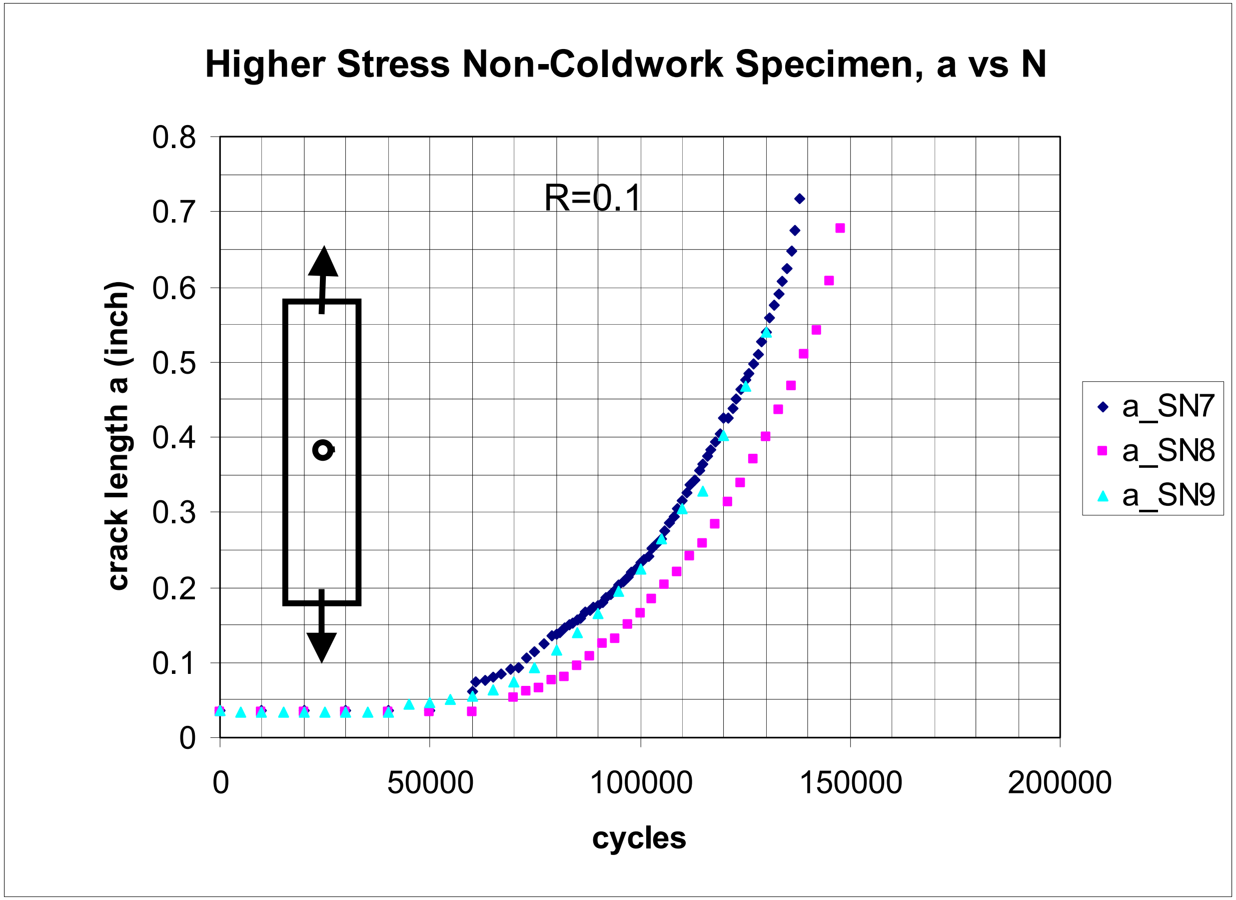
.312/2 +.010 =.165” (no crack at 1e6 cycles)

.344/2 +.010 = .182” (next test specimen)

7.2 ksi Lower-Stress Non-Cold Worked Specimens (P=polished)



9.25 ksi Higher-Stress Non-Cold Worked Specimens



All specimens Polished at notch

Test Matrix: Non-cold worked and cold worked specimens

Specimen Thickness (in)	Condition	EDM Notch	Approximate EDM Notch Size **	Number of Specimens	Number of Spares	Number of Specimens Tested	Applied Max Load (lb)	Load Ratio
0.08	non-cold worked	thru thickness	0.010	3	3	0	MSU	MSU
0.08	non-cold worked	thru thickness	0.010	3		0	MSU	MSU
0.08	cold worked	thru thickness	0.010	3	3	4 *a	TBD	0.1
0.08	cold worked	thru thickness	0.010	3		0	TBD	0.1
0.19	non-cold worked	corner	0.030	3	3	5	2362 *b	0.1
0.19	non-cold worked	corner	0.030	3		3	3222 *c	0.1
0.19	cold worked	corner	0.030	3	3	0	TBD	0.1
0.19	cold worked	corner	0.030	3		0	TBD	0.1
TBD	laser peen	TBD	TBD	TBD	TBD	0	TBD	TBD
			Total	24	12	8		

*a: 2 at MSU (unrepresentative failures), 2 at Sikorsky (after 1e6 cycles, crack stopped or did not occur)

*b: 7.2 ksi gross stress (far field)

*c: 9.25 ksi gross stress

** EDM notch size is defined as radial length from hole true edge to corner of notch at specimen surface